EFFECT OF POLYURETHANE WITH REFINED COAL ON HIGH-STRENGTH MORTAR

EFEITO DO POLIURETANO COM CARVÃO REFINADO EM ARGAMASSA DE ALTA RESISTÊNCIA

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Abstract: This article investigates the influence of adding polyurethane with refined coal to high-strength mortar, evaluating its mechanical and physics. The tests conducted for this study included X-ray diffraction, compressive strength, elastic modulus, and tensile strength. Results showed that the compressive strength of the mortar decreased when refined coal was incorporated into the reference mortar, and the inclusion of polyurethane in this mixture led to a further reduction in compressive strength. Additionally, a decrease in the elastic modulus was observed with the addition of refined coal, and the inclusion of polyurethane in this mixture caused an additional reduction. The porosity of the mortar significantly increased with the addition of polyurethane to the mortar containing refined coal. In summary, adding polyurethane and refined coal to high-strength mortar compromises its mechanical properties, particularly through a re-duction in compressive strength, elastic modulus, tensile strength, and an increase in porosity. Although polyurethane contributes to flexibility and adhesion between particles, its interaction with refined coal creates a more porous structure, potentially impairing the material's durability and strength.

Keywords: High-strength mortar. Sustainability. Compressive strength. Elastic modulus. Tensile strength. Porosity.

Resumo: Este artigo investiga a influência da adição de poliuretano com carvão refinado em argamassas de alta resistência, avaliando suas propriedades mecânicas e físicas. Os testes realizados para este estudo incluíram difração de raios X, resistência à compressão, módulo de elasticidade e resistência à tração. Os resultados mostraram que a resistência à compressão da argamassa diminuiu quando o carvão refinado foi incorporado à argamassa de referência, e a inclusão de poliuretano nesta mistura levou a uma redução adicional na resistência à compressão. Adicionalmente, foi observada uma diminuição no módulo de elasticidade com a adição de carvão refinado, e a inclusão de poliuretano nesta mistura causou uma redução adicional. A porosidade da argamassa aumentou significativamente com a adição de poliuretano à argamassa contendo carvão refinado. Em resumo, a adição de poliuretano e carvão refinado a argamassas de alta resistência compromete as suas propriedades mecânicas, nomeadamente através da redução da resistência à compressão, do módulo de elasticidade, da resistência à tração e do aumento da porosidade. Embora o poliuretano contribua para a flexibilidade e adesão entre as partículas, a sua interação com o carvão refinado cria uma estrutura mais porosa, prejudicando potencialmente a durabilidade e resistência do material.

Palavras-chave: Argamassa de alta resistência. Sustentabilidade. Resistência à compressão. Módulo elástico. Resistência à tração. Porosidade.

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1 INTRODUCTION

In the construction industry, cement is one of the most widely used materials worldwide due to its various applications in buildings. With the exponential increase in population, a parallel growth in cement-based compounds consumption is observed. In response to this demand, the cement industry has been continually striving to enhance the physical and chemical properties of cement derivatives. This pursuit of improvements dates back to pre-recorded history when additives were already incorporated into cementitious mixtures to optimize their mechanical properties. Such innovations are essential to meet the durability and performance requirements of modern construction materials (J. *et al.*, 2023).

Mortar is a material composed of cement, water, and sand, widely used in the construction industry, especially for coatings and as a binding agent in the laying of bricks and blocks in wall construction. Beyond its conventional functions, mortar can also be ed structurally, playing a significant role in the strength and stability of buildings.

This versatility makes mortar an essential component in various application contexts, contributing to both the aesthetics and structural integrity of constructions (JONNALA *et al.*, 2024, 18-05B; TESTING, 2020).

One of the main challenges in construction is ensuring the durability and strength of structures. The use of conventional materials often results in significant problems, such as the formation of cracks in structures exposed to climatic variations and excessive loads, compromising structural integrity (JÚLIO; BOGAS; COSTA, 2022).

Additionally, conventional mortar may experience premature wear, deteriorating quickly and requiring frequent repairs, which increases maintenance costs over time. In projects requiring support for high loads, standard mortar may have a limited load-bearing capacity, failing to meet necessary requirements and leading to structural failures. These issues underscore the importance of developing and employing innovative solutions that can enhance construction strength and durability (FRIGIONE; AGUIAR, 2020).

A prominent emerging method in the application of mortars and other cement derivatives, such as concrete, is the high-strength technique. This method involves modifying the compound's mix composition, resulting in a final product that does not require consolidation during application. In other words, mechanical vibration is not necessary to ensure mortar settling. This feature not only broadens the range of possible applications for mortar but also facilitates maintenance during the curing period, contributing to greater efficiency and practicality in construction projects. The adoption of this method represents a significant advancement in construction material technology,

promoting more effective and durable solutions (VITORINO; SILVA, 2021).

High-strength mortar is a material specifically designed to support high loads, providing greater durability and stability in constructions. Its composition is based on a mix of cement, sand, and specific additives that enhance its mechanical properties. Among the main advantages of high-strength mortar is its high durability, offering greater resistance to adverse weather conditions and wear, thus extending the structure's lifespan (NAJEEB; MOSABERPANAH, 2023).

Moreover, high-strength mortar has significant load-bearing capacity, making it ideal for applications in structures that need to withstand heavy weights, such as slabs and pillars, ensuring building safety and stability (PREETHI; KUMAR; HAMRAJ, 2019) .

Another important characteristic of this type of mortar is its reduced susceptibility to cracks, which results in fewer occurrences of cracking, preserving both the aesthetic and structural integrity of the material.

These qualities make high-strength mortar a preferred choice for construction projects requiring superior performance and reliability (NGO; NGUYEN; NGUYEN, 2022). Currently, the use of high-strength cement derivatives has become predominant in large-scale constructions. This trend reflects the pursuit of materials that ensure greater durability, strength, and safety in buildings (FERNÁNDEZ-MUÑIZ *et al.*, 2024)

As the benefits associated with high-strength mortars become more evident, there is growing interest in their application in smaller constructions as well. This shift could result in significant improvements in the mechanical properties and longevity of structures, advancing construction practices. Thus, the adoption of high-strength mortars in smaller-scale projects represents a continuation of innovation in the construction sector, contributing to building efficiency and sustainability (RUANO GUTIÉRREZ *et al.*, 2024).

In this research, sustainable materials were applied with the goal of synthesizing an eco-friendly mortar, utilizing coal derived primarily from plantation-grown wood, with eucalyptus as the main reforested species. The origin of the materials used is a critical factor in assessing the sustainability of the final product.

Furthermore, an innovative aspect of this study is the use of an electrolysis method for additive production, which is relatively cheaper and involves lower energy costs than conventional methods, making industrial-scale synthesis feasible (SOLTANINEJAD *et al.*, 2021).

The effects of polyurethane were also examined, with civil engineering responsible for over a third of this polymer's market use. The choice of polyurethane is due to its versatility, exhibiting properties of both metals and rubbers (ZHANG *et al.*, 2021b).

This study employed sustainable materials to synthesize an eco-friendly mortar.

Coal was used, largely sourced from reforested wood, with eucalyptus as the main species. The origin of the materials used is a critical factor in assessing the sustainability of the final product.

Additionally, an innovative aspect of this study is the use of the electrolysis method for obtaining the additive, which is relatively more economical and energy-efficient compared to conventional methods. This approach not only reduces production costs but also makes industrial-scale synthesis feasible.

This research, therefore, contributes to developing construction solutions that promote sustainability and reduce environmental impact in the construction industry.

The primary objective of this study is to investigate the impact of adding polyurethane with refined coal on the properties of high-strength mortar. Specifically, it aims to evaluate changes in the mechanical properties and durability of the composite material. Furthermore, it seeks to assess the technical and economic feasibility of using this combination, aiming to contribute to innovation in the construction industry.

2 MATERIALS AND METHODS

2.1 Refined Coal

To obtain the refined coal, pieces of coal with an electrical resistance below 30 Ω were initially selected. This measurement was conducted using an Exbom multimeter, model "MD-180L," to ensure the selection of materials with suitable electrical properties.

After selection, the coal pieces were ground using an agate mortar and pestle to create a fine powder. This grinding process ensures uniform particle size, which is essential for subsequent stages.

The resulting powder was then sieved using two mesh screens with 0.5 mm diameters. This step aimed to separate any larger fragments that were not adequately ground, allowing them to be returned to the agate mortar for additional grinding.

The fine powder that passed through the sieve was prepared for the electrolysis stage, where it would undergo an exfoliation process. For the reaction, a 1 mol/L sulfuric acid (H_2SO_4) solution was prepared, using distilled water as the solvent, to serve as the medium for electrolysis (XIA *et al.*, 2021).

Next, for the electrolysis preparation, 1 g of refined coal powder was added to 40 ml of sulfuric acid solution. This ratio was carefully maintained across all samples, ensuring a consistent 1 g of coal per 40 ml of solution. The resulting mixture was homogenized to ensure that the coal was well-dispersed in the acidic solution, a key requirement for the efficiency of the electrolytic process. This initial preparation established the necessary

conditions for electrolysis, facilitating adequate interaction between the coal and sulfuric acid during the process.

In the electrolysis process, platinum electrodes were used to prevent any undesired interaction between the acid and the electrodes, thereby ensuring the system's stability and efficiency. Electrolysis was conducted for three minutes, during which an electric current was applied to the acidic solution, prompting chemical reactions at the electrodes. After completing the electrolytic process, the material, which still contained acid, was filtered.

A paper filter placed in a funnel was used to separate the solids from the liquid. The filtered liquid was then washed with distilled water to remove any acidic residue until a neutral pH was reached, a crucial step to ensure the complete removal of acid and the safety of the final material.

The material obtained was then subjected to a drying process in an oven at a temperature of 100 °C for 24 hours.

This step is critical to remove any moisture from the refined coal powder, ensuring that the material is dry and free of any solvent that might interfere with subsequent stages. Once the drying process was complete, the material was carefully stored in a beaker, ready for use in subsequent processes. This storage approach ensures that the refined coal retains its properties and is ready for use in planned reactions or experiments.

To obtain the material composed of refined coal and polyurethane, a procedure similar to that used for pure refined coal was followed. However, in this step, 0.5 g of polyurethane and 0.5 g of coal were used, substituting the total amount of 1.0 g of coal.

After mixing the components, the resulting material was dried in an oven at 100 °C for 24 hours. At the end of this period, the material appeared homogenous, with no distinct two-phase appearance, indicating that the polyurethane had effectively incorporated the refined coal, forming a uniform matrix.

Visually, the two samples displayed distinct characteristics in terms of color. While the pure refined coal powder was a deep black, the material obtained with the addition of polyurethane exhibited a lighter color, with a grayish-black hue. This color difference suggests an interaction between the components, resulting in a composite material with unique properties.

2.2 Mortar

To determine the specific mass of fine aggregate, the procedure established by the standard was used ABNT NBR 52 (2009). The cement utilized in the experiment was CP-

II-E-32, characterized following the procedures outlined in ABNT NBR 17054 (2022) and ABNT NBR16605 (2017). These standards specify methods for evaluating cement properties to ensure the material meets required standards. In addition to cement, metakaolin was incorporated as part of the fines in the mix.

The amount of metakaolin used was carefully calculated to correspond to 10% of the total mass of cement, resulting in 1,031.30 g of cement and an addition of 103.13 g of metakaolin. This ratio was chosen to improve material properties such as workability and durability. Metakaolin acts as a pozzolanic mineral, contributing to reactions that enhance concrete strength (KAMAL *et al.*, 2024;TRENTIN *et al.*, 2022).

The mixture was then prepared with precise proportions of cement and metakaolin, following proper mixing procedures to ensure a homogeneous blend before proceeding with the subsequent stages of the experiment. A total of 544 g of water was used in preparing the mortar to ensure adequate hydration and desired consistency. To achieve a high-strength mortar, a superplasticizer (SP) was added to the mix. This chemical additive primarily enhances the mortar's fluidity and cohesion, improving workability and eliminating the need for mechanical vibrators during application.

The superplasticizer selected was from the ADITIBRAS brand, specifically from the RX line, classified as a Type RA2 Superplasticizer. This product was supplied as a sample by the company, ensuring the quality and effectiveness of the additive for mortar formulation. The superplasticizer was added according to the manufacturer's recommendations to optimize the mortar's properties.

This combination of water and superplasticizer significantly contributes to the final material performance, resulting in high-strength mortar with improved application characteristics.

After separating the materials for the batch with their pre-determined quantities, the mixing process began. All fine aggregates, including cement and metakaolin, were added to the mixer. The powders were mixed with a spoon until a homogeneous blend was obtained, ensuring component uniformity. Next, approximately 65% of the calculated water was added, and the mixture was stirred with a spoon to form a consistent paste. Following this, the superplasticizer was added, followed by the remaining water. The mixture was stirred again, resulting in a liquid consistency essential for mortar workability.

In the next step, sand was gradually incorporated into the mixture while stirring continued. This controlled addition allows for the proper integration of sand into the mix, ensuring a homogeneous mortar. Water was added as needed to adjust consistency until the desired mortar properties were achieved.

The resulting material was transferred to the mortar mixer, where it was processed

at low speed for 3 minutes, a step critical to ensuring all components were well incorporated. After this time, the mortar was left to rest for 1 minute, allowing any air bubbles to dissipate and the mix to stabilize. Stirring resumed for another 2 minutes to ensure proper mortar homogeneity.

Once mixing was complete, cylindrical molds were prepared with a mix ratio of 1.03:1.42:1.43:0.10:0.54:0.39, corresponding to the proportions of cement, medium sand, fine sand, metakaolin, water, and superplasticizer, respectively.

First, the 5 cm diameter by 10 cm height cylinders were lubricated to facilitate mortar removal after curing. The empty cylinders were then weighed to record their initial mass.

The cylinders were filled to the top with mortar and weighed again. This weighing is crucial for calculating the mortar's specific mass by using the weight difference between full and empty cylinders.

Other mortar batches were prepared similarly. However, for formulations containing pure refined coal and polyurethane, a proportion of 1% of the cement mass was adopted, equivalent to 10.31 g, with the same amount of metakaolin subtracted. The scale used for weighing had a tolerance error of 0.05 g, ensuring precise measurements.

According to the NBR 5738 (2018) standard, specimens were molded in cylindrical molds with a 15 cm diameter and a 30 cm height. After 24 hours, the specimens were de-molded and stored in a moist chamber with lime, where they remained for a curing period of 28 days.

For the compression resistance test, six specimens were molded for each mix, following the procedures outlined in ABNT NBR 5739 (2018), which describes the methodology for performing compression tests on cylindrical concrete specimens molded per NBR 5738 (2018)

To evaluate the modulus of elasticity, six specimens were molded for each mix, according to the procedures outlined in ABNT NBR 6118 (2023) and ABNT NBR 8522 (2021). For the split tensile test, six specimens were prepared by ABNT NBR 5739 (2018) and ABNT NBR 6118 (2023).

In the direct tension test, the sample ends are fixed, and all parts of the hinge system are threaded to prevent rotation. While the system is considered unique and stable, it is crucial to ensure the correct alignment of the sample during the initial setup to avoid eccentricities. This procedure is essential to ensure that the induced stress is purely direct tension during loading, especially in the post-cracking regime of the composites.

The material's porosity was assessed based on compression: resistance values, using an empirical relationship known as the Powers equation (ZHENG *et al.*, 2023). This

equation establishes a correlation between compressive strength (fc) and material porosity (ϕ).

$$\phi = 1 - \left(\frac{f_c}{f_{c0}}\right)^{1/n}$$

To facilitate calculations, it is common to assume a compressive strength value for non-porous concrete, denoted as fc_0. In the absence of a specific value, a commonly used empirical constant is applied; for this study, fc_0=40 MPa, is considered, a value frequently adopted for high-strength concretes. Additionally, n=2, is assumed, allowing the use of a simplified form of Powers' equation to determine the material's porosity (ZHENG *et al.*, 2023).

The reference mortar samples with refined coal and polyurethane-refined coal were analyzed using X-ray diffraction (XRD) in a fine powder form. This test involves the incidence of an X-ray beam that interacts with the crystalline planes of the sample, altering its propagation direction and generating a spectrum that reflects the crystallinity characteristics of the sample. During sample characterization, the equipment operated with a CuKα radiation source (λ = 1.5418 Å), at a voltage of 40 kV and a current of 15 mA, in 2θ mode, within a scan range of 5° to 80°, step size of 0.02°, and step time of 1.0 s. The phases present in the sample were investigated using X'Pert HighScore Plus software, which employs a crystallographic pattern database for identifying and analyzing crystalline structures.

3 RESULTS AND DISCUSSION

Table 1 presents the values of the particle size distribution of the fine aggregate. The fineness modulus (FM) determined for the fine aggregate was 2.95. According to the NBR 7211 (2022) (NBR7211, 2022) standard, this value falls within the range that classifies the fine aggregate as medium sand, where the classification range is established as 2.4 < FM < 3.3 (NBR7211, 2022).

With an FM of 2.95, the aggregate is situated close to the upper limit of the medium sand classification. This characterization indicates a particle size distribution that enhances the workability of concrete, allowing for a reduction in cement consumption without compromising the material's strength.

Table 1 - Particle Size Distribution of the Fine Aggregate

Siave	% Passing	% Retained	% Cumulative Retained
4.8	100	0	0
2.4	88	12	12
1.2	65	23	35
0.6	38	27	62
0.3	12	26	88
0.15	2	10	98
Fundo	0	2	100
Specific Gravity of Aggregate (g/cm³)	2.75	100 Fineness Modulus:	2.95
Apparent Dry Specific Gravity (g/cm³)	2.65	Maximum Diameter (mm)	2.4

Figure 1 illustrates the particle size curves of the analyzed sand, demonstrating that the particle size distribution falls within the upper optimal range for most of the interval. This indicates that the particle size distribution of the sample is within an acceptable range for various applications. The fineness modulus of the sample, which is between 2.20 and 2.90, supports this classification.

According to the data presented in Table 1, the maximum diameter of the particle size composition was determined to be 4.8 mm, based on the criterion that the maximum diameter should be associated with a cumulative retention percentage of less than 5% (LU *et al.*, 2024). This parameter is crucial for characterizing the physical properties of the sand in question, contributing to the understanding of its suitability for specific engineering applications.

Figure 1 - Particle Size Distribution Curve of the Sand

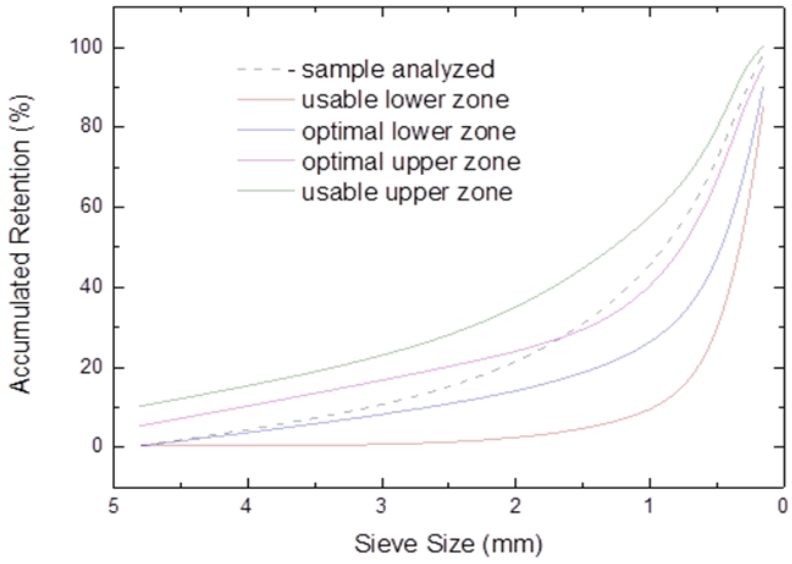


Figure 2 presents a comparative analysis of three types of specimens, as illustrated in subfigures (a) to (c). Subfigure (a) displays the reference specimen, which serves as a base-line for comparative evaluation. Subfigure (b) presents a specimen that incorporates re-fined coal, a material that has been extensively studied due to its beneficial properties.

Lastly, subfigure (c) demonstrates a specimen consisting of a combination of polyurethane (PU) waste and refined coal, referred to as (EC+POL), highlighting the synergy between these two materials. In subfigure (a), the presence of cracks and porosity in its structure suggests the occurrence of failures or weaknesses in the reference specimen, aspects that may impact its performance in practical applications. Subfigures (b) and (c) present, respectively, the specimens that incorporate refined coal and the mixture of polyurethane (PU) waste with refined coal, designated as EC+POL. In both subfigures, a predominance of porosities in the structure of the specimens can be observed, while no evident signs of cracks are identified.

This characteristic suggests a relatively more favorable structural integrity compared to the reference specimen, which may imply enhanced performance in applications re-quiring materials with properties of strength and durability.

Figure 2 - a) reference specimen, b) specimen with refined coal, and c) specimen with refined coal and polyurethane.

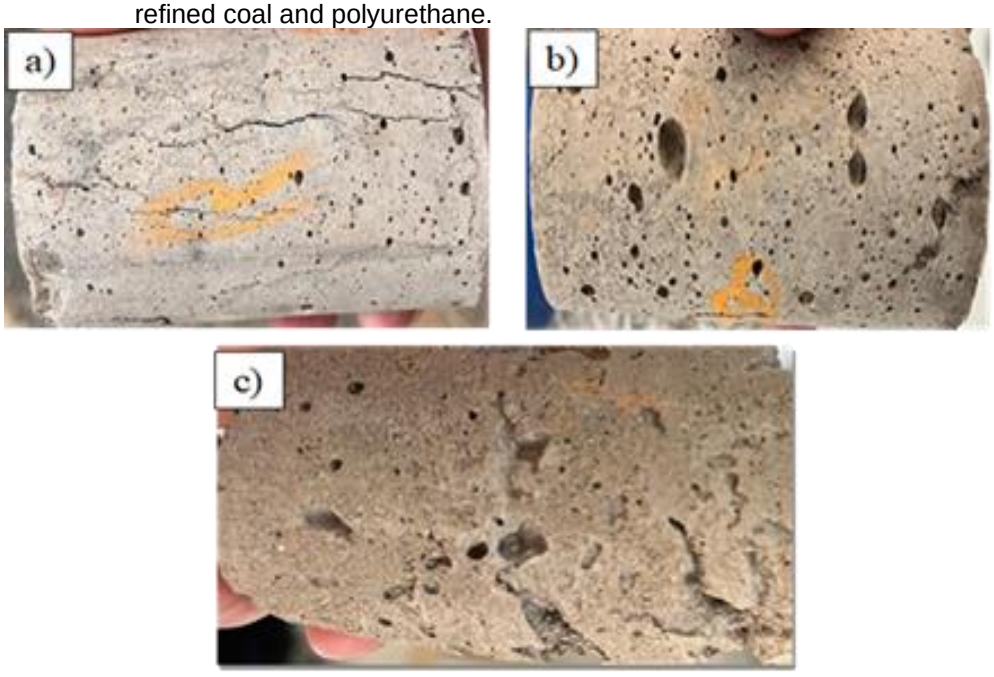


Figure 3 shows the X-ray diffraction (XRD) of the reference mortar containing silicon dioxide (SiO_2), benzoquinone, and calcium silicate ($CaSiO_3$). Silicon dioxide, often present in the form of sand or as a component of cement, plays a fundamental role in the formation of hydrated calcium silicate gel (C-S-H), which is responsible for the strength

and durability of the mortar, significantly contributing to its cohesion and structural integrity (TANG *et al.*, 2021).

Benzoquinone, although an organic compound, is added as a chemical additive, acting as a bonding agent that improves the adhesion and strength of the material, similar to a superplasticizer. Calcium silicate, present as a component of cement or formed during hydration, is crucial for the development of strength, as it participates in the formation of C-S-H during the hydration reaction, thereby improving the durability and compressive strength of the mortar (TANG *et al.*, 2021).

The interaction between these components, evidenced by the XRD, reveals the structural complexity of the mortar and highlights the importance of each element in optimizing the material properties for construction applications.

The X-ray diffractogram of the mortar containing refined coal indicates the presence of components such as calcium coalate ($CaCO_3$), silicon dioxide (SiO_2), coal (C), and coal oxide (CO). Calcium coalate serves as a filler that improves the workability and strength of the mortar, while silicon dioxide contributes to the formation of hydrated calcium silicate gel (C-S-H), essential for mechanical strength. However, the introduction of coal, while not improving mechanical properties, increased material porosity (WANG, L. *et al.*, 2019). This increase in porosity may negatively impact the compressive strength and durability of the mortar, as a more porous structure can facilitate moisture penetration and aggressive agents. Additionally, coal oxide, generated during chemical reactions, may also affect the material's microstructure.

Firstly, the presence of CO can influence the formation of porosity. During cement hydration, it can lead to the creation of voids that, at excessive levels, increase porosity and reduce the material's density. Furthermore, coal oxide may interact with other mortar components, altering the dynamics of the chemical reactions that occur during curing. This interaction can affect the hydration rate and the formation of hydrated products, such as calcium silicates, which are crucial for the mortar's final strength (YASEEN; YISEEN; LI, 2019).

The X-ray diffractogram of the mortar containing refined coal and polyurethane, with the addition of silicon dioxide (SiO_2), coal (C), calcium coalate ($CaCO_3$), coal dioxide (CO_2), coal C_{60} (fullerene), and C_4O_8, reveals a complex interaction between these phases. Silicon dioxide is essential for the development of hydrated calcium silicate gel (C-S-H), contributing to the mechanical strength and durability of the mortar. Calcium coalate, besides acting as a filler, can influence the reactivity of the system and the formation of hydrated products.

The presence of coal dioxide suggests chemical reactions that may occur during the curing process, potentially affecting the final microstructure of the material. Coal C_{60}, known for its unique structural properties, may enhance tensile strength and mechanical stability, while the chemical formula C_4O_8 indicates the possibility of forming complex organic compounds that may influence the rheological behavior of the mortar.

Figure 3- X-ray diffractograms of the reference specimen, specimen with refined coal, and specimen with refined coal and polyurethane.

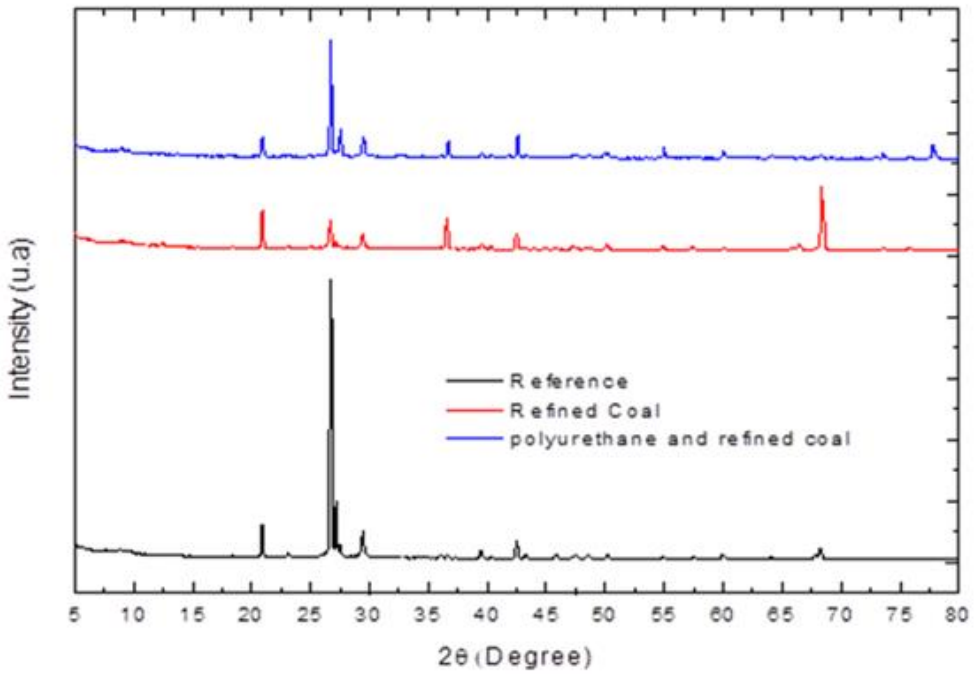


Figure 4 illustrates the specimens fractured after 28 days of curing, as a result of the compressive strength test. Additionally, Figure 4 presents the stress-strain curve for the mortars, covering three different compositions: the reference specimen, the specimen containing only refined coal (EC), and, finally, the combination of refined coal with polyurethane (EC+POL). These graphical representations are essential for evaluating the mechanical behavior of the materials, enabling a comparative analysis of the performance of each mix under load conditions.

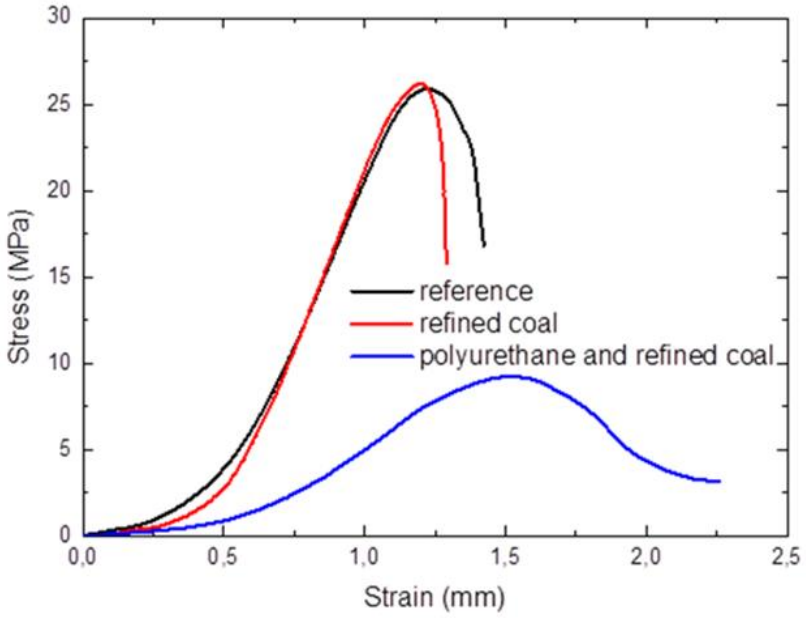
Figure 4- Specimens fractured in the compressive strength test

In Figure 5, it was observed that both the reference mix and the mix with refined coal additive (EC) displayed compressive strengths close to 25 MPa, with maximum stress averages of 27.49 MPa and 23.91 MPa, respectively. In contrast, the mix incorporating poly-urethane (POL) showed a significant reduction in compressive strength, presenting a value of 10.27 MPa, less than half the anticipated strength.

Although the exact causes of this sharp decrease in stress cannot be definitively pin-pointed, a notable observation in the samples suggests substantially higher water absorption in formulations containing both polymer and coal.

This excessive absorption may have introduced air into the specimen, resulting in increased fragility of the mortar, compromising its structural integrity and, consequently, its performance under load.

Figure 5 - Stress-Strain Graph of the Average for Each Sample



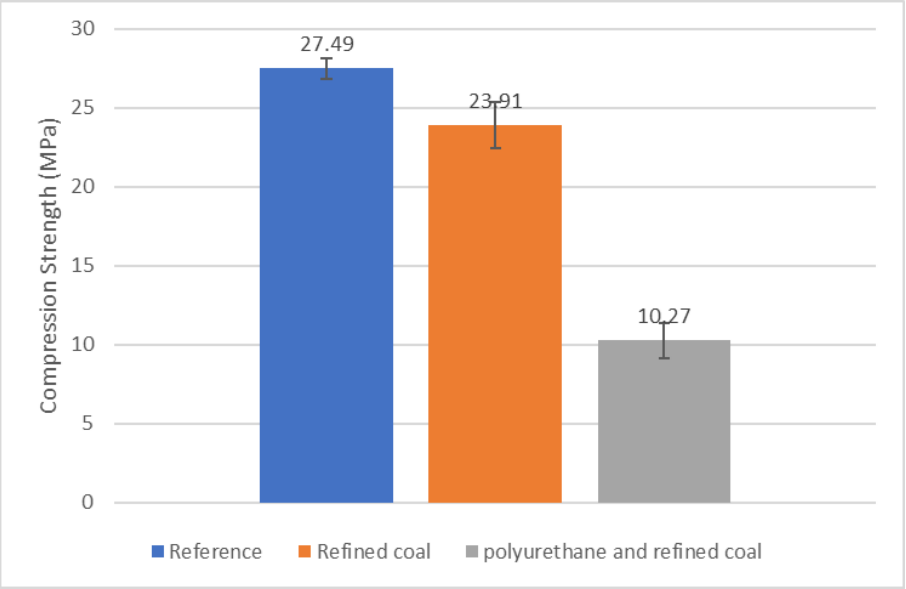
The results shown in Figure 6 indicate a significant reduction in the compressive strength of the mortar due to the addition of different components. The compressive strength decreased from 27.49±0.67 MPa to 23.91±1.45 MPa upon incorporating refined coal into the reference mortar. Furthermore, adding polyurethane to the mortar already containing refined coal led to a further reduction, with the compressive strength reaching 10.27±1.13 MPa.

These data highlight that both refined coal and polyurethane negatively impact the mechanical strength of the mortar, underscoring the need for in-depth analysis regarding the interaction of these materials in mortar compositions intended for structural applications. The observed decrease in compressive strength with the addition of refined coal to the reference mortar can be attributed to increased matrix porosity. The presence of refined coal tends to increase the number of pores, as well as alter their distribution, shape, and size (LEÓN *et al.*, 2022). This change in the mortar's microstructure compromises its ability to effectively transmit stress, resulting in decreased mechanical strength.

The increased porosity may also create preferred failure paths under load, emphasizing the need for a more detailed analysis of refined coal's effects on the mortar's physical and mechanical properties (WANG, Y. *et al.*, 2022).

The reduction in compressive strength observed in the mortar containing both polyurethane and refined coal can be explained by the synergy between these materials, which amplifies their adverse effects on the composite's mechanical properties. Both polyurethane and refined coal contribute to reducing adhesion between the mortar particles, thereby compromising the material's internal cohesion. Additionally, the combination of these components results in increased porosity and changes in the mortar's microstructural framework (ZHANG *et al.*, 2021a). These factors exacerbate the matrix's vulnerability to failure under load, highlighting the importance of a careful balance in formulating mortars that incorporate additives like polyurethane (AL-KAHTANI *et al.*, 2022).

Figure 6- Compressive Strength of the Reference Specimen, Specimen with Refined Coal, and Specimen with Refined Coal and Polyurethane



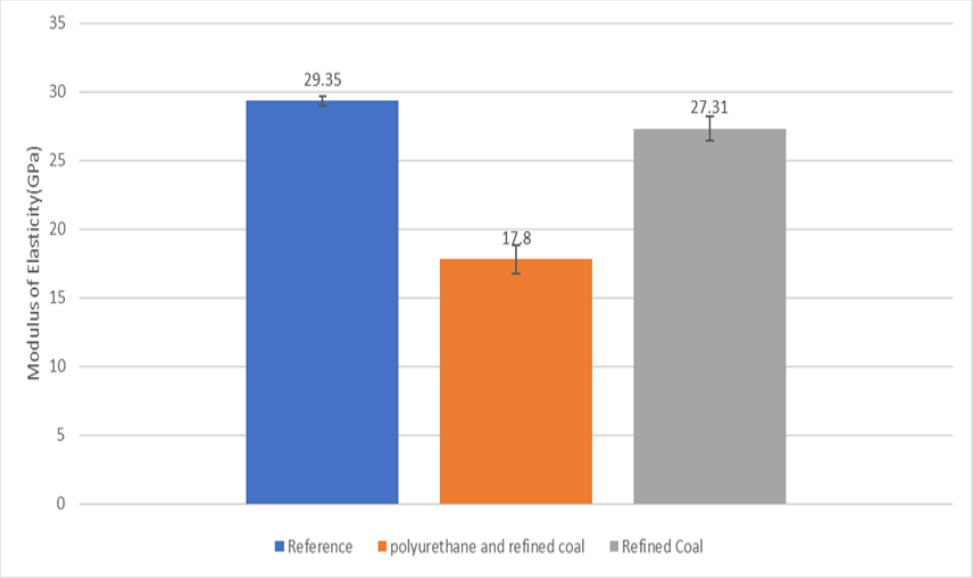
The results obtained in Figure 7 reveal a decrease in the elastic modulus of the mortar, which varied from 29.35 ± 0.36 MPa to 27.31 ± 0.88 MPa with the addition of refined coal to the reference mortar.

This reduction can be attributed to the increase in porosity caused by the incorporation of refined coal, which creates voids and consequently reduces the contact area between the constituent particles of the cement matrix. Furthermore, the fine particles of refined coal may not disperse uniformly among the other components of the mortar, resulting in the formation of areas with lower density and higher porosity.

These low-density areas act as weak points, compromising the mortar's ability to resist deformation, as discussed by RIBEIRO *et al.* (2022). It was observed that the elastic modulus of the mortar decreased from 27.31 ± 0.88 MPa to 17.80 ± 1.04 MPa with the addition of polyurethane to the mortar that already contained refined coal.

This pronounced decrease can be attributed to the combination of polyurethane and refined coal, which enhances the lubricating effect between the particles, resulting in reduced friction and, consequently, decreased resistance of the cement matrix. The interface formed between the polyurethane, refined coal, and the other components of the mortar may give rise to areas of lower adhesion, acting as weak points. This deterioration in mechanical properties underscores the importance of careful consideration in the formulation of composites that utilize these materials to optimize their structural performance (RIBEIRO *et al.*, 2022).

Figure 7- Elastic modulus of the reference specimen, specimen with refined coal, and specimen with refined coal and polyurethane.



The results presented in Figure 8 indicate a significant reduction in the tensile strength of the analyzed material, which decreased from (2.76±0.04) MPa to (2.51±0.10) MPa with the addition of refined coal to the reference mortar. This decrease can be attributed to an increase in the porosity of the concrete, a consequence of the incorporation of coal, which introduces voids into the material matrix (ZHANG *et al.*, 2021b). This phenomenon compromises the concrete's ability to withstand stresses, as excessive porosity can adversely affect structural integrity. Furthermore, refined coal may interfere with the hydration process of the cement, altering the formation of the cement paste and the adhesion between the different components of the mixture. Such interference results in a less cohesive structure, which may explain the observed decrease in tensile strength. Thus, it is evident that the inclusion of refined coal requires careful analysis of its effects on the mechanical properties of concrete (MANGI *et al.*, 2018) .

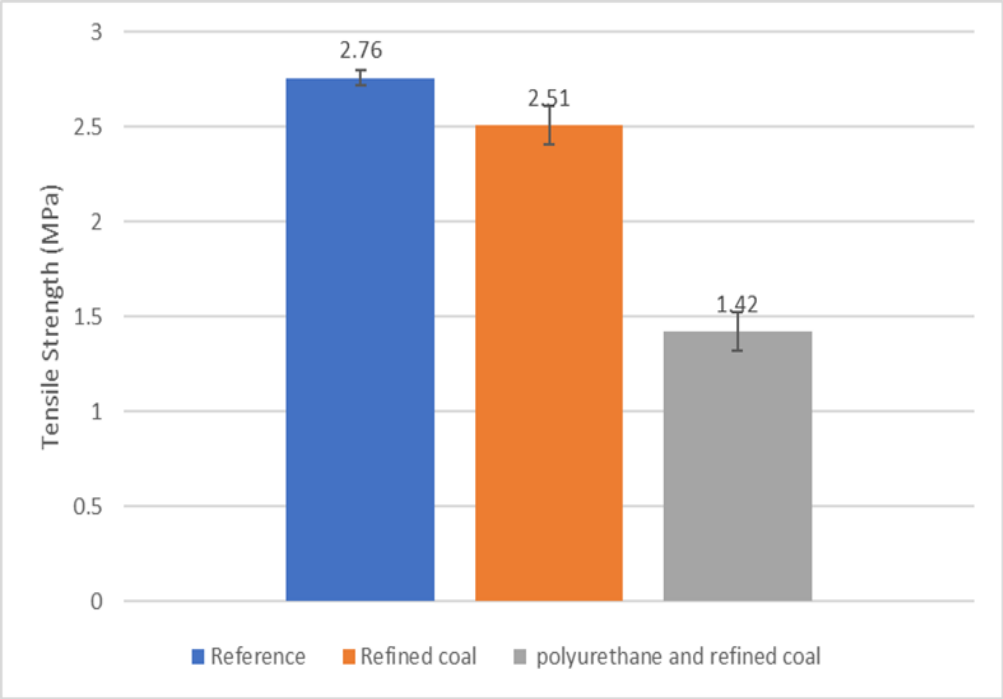
The obtained data also indicate an additional reduction in the tensile strength of the mortar, which fell from (2.51±0.10) MPa to (1.42±0.10) MPa with the incorporation of polyurethane into the mixture that already contained refined coal. This decrease in strength can be attributed to the interference of polyurethane in the interaction between the cement grains and the other components of the mortar.

The presence of polyurethane tends to compromise the cohesion of the matrix, resulting in a less solid structure and, consequently, more vulnerability to mechanical failure (ZHANG *et al.*, 2021b). The degradation of the bond between the cement grains can lead to an inadequate distribution of stresses, increasing the material's susceptibility

to fractures under load.

Thus, the addition of polyurethane in systems that already exhibit increased porosity, such as the mixture with refined coal, requires critical consideration of its implications for the structural integrity of the composite (ZHANG *et al.*, 2021b).

Figure 8 - Tensile strength of the reference specimen, specimen with refined coal, and specimen with refined coal and polyurethane

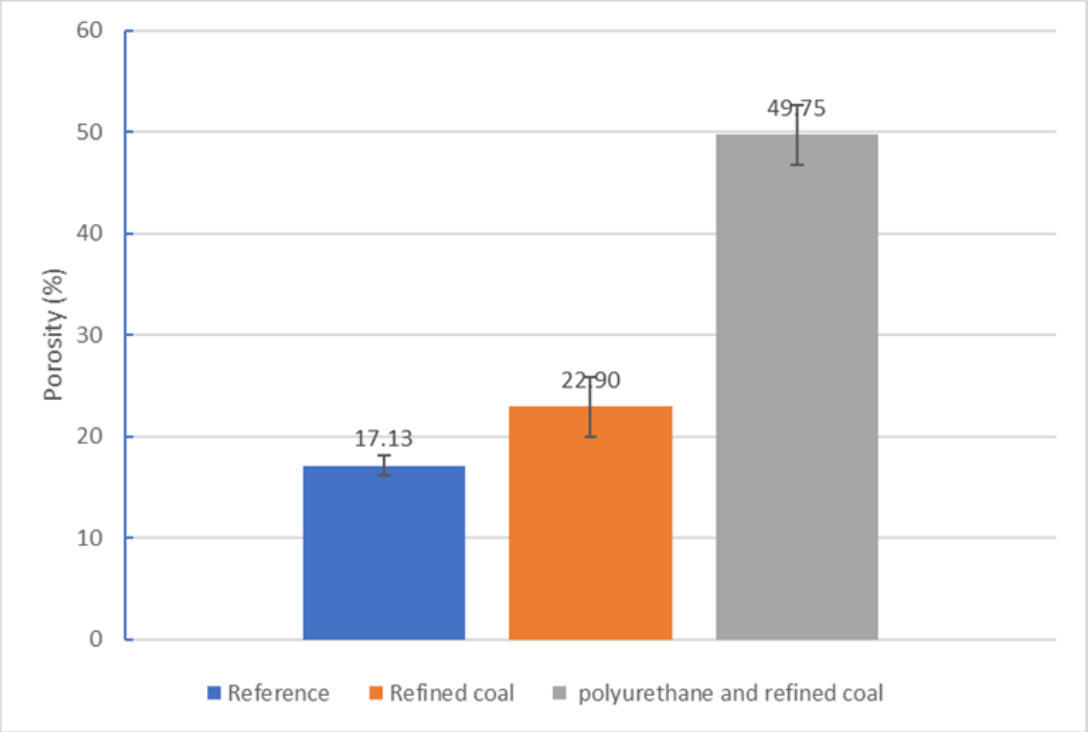


Based on the results shown in Figure 9, it was observed that porosity increased from (17.13 ± 1.01) MPa to (22.90 ± 2.50) MPa upon adding refined coal to the reference mortar. The increase in porosity due to the addition of refined coal can be explained by its porous structure, which can contribute to the formation of voids in the mortar, resulting in higher porosity. Additionally, the chemical interactions of the coal may interfere with the chemical reactions during the curing of the mortar, altering how the components bond and resulting in a more porous microstructure (POKORNÝ *et al.*, 2023).

It was also noted that porosity increased from (22.90 ± 2.50) MPa to (49.75 ± 2.94) MPa upon adding polyurethane to the mortar containing refined coal.

The increase in porosity due to the addition of polyurethane to the mortar that already contains refined coal can be attributed to interactions with the refined coal. The presence of refined coal may alter how polyurethane interacts with the mortar, enhancing the formation of voids and increasing overall porosity. Furthermore, the density reduction caused by polyurethane may create more voids within the structure, contributing to an increase in porosity.

Figure 9 - Porosity of the reference specimen, specimen with refined coal and specimen with refined coal and polyurethane



4 CONCLUSIONS

The addition of polyurethane and refined charcoal to high-strength mortar results in a compromise of mechanical properties, notably characterized by a reduction in compressive strength and elastic modulus, as well as an increase in porosity. While polyurethane contributes to flexibility and adhesion between particles, its interaction with refined char-coal leads to a more porous structure.

This alteration may compromise the durability and strength of the material, limiting its applicability in demanding structural contexts.

Furthermore, the decrease in tensile strength observed with the addition of both components indicates that, although there may be benefits in terms of workability and performance under certain conditions, the negative impact on mechanical properties is a significant concern. These findings suggest that to maximize the benefits of polyurethane and refined charcoal, a careful balance in the formulation of the mortar is essential.

Therefore, further studies are recommended to explore different proportions and methods for incorporating these additives, aiming to optimize the properties of the mortar. Identifying possible alternatives or modifications in the formulation could result in materials that not only maintain the advantages of flexibility and adhesion but also preserve or even enhance strength and durability, ensuring adequate performance in structural ap-

plications. Continued research in this area is crucial for the development of innovative and effective solutions in civil engineering.

The incorporation of metakaolin has shown potential for increasing the compressive strength of the mortar. Metakaolin, being a pozzolanic material, reacts with free lime and improves the formation of calcium silicate hydrate (C-S-H) gel, contributing to a denser and more resilient matrix

Therefore, the combination of metakaolin with polyurethane and refined charcoal could offer an interesting solution to optimize mechanical properties, potentially mitigating the negative effects observed. However, the introduction of metakaolin in the formulation was insufficient to increase compressive strength, indicating that its expected efficacy as a pozzolanic material did not manifest as desired in this context. This suggests that the interaction between metakaolin, polyurethane, and refined charcoal may not have pro-moted the necessary chemical reactions to form a denser and more resistant matrix.

In light of this, additional studies are recommended to explore different proportions and methods for incorporating metakaolin alongside the other additives. Identifying synergies among these components could result in formulations that not only retain the bene-fits of flexibility and adhesion but also enhance the strength and durability of the mortar. Continued research in this area is crucial for the development of innovative and effective solutions in civil engineering.

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